PRRC 94-26

Quarterly Technical Progress Report

IMPROVED EFFICIENCY OF MISCIBLE CO_2 FLOODS AND ENHANCED PROSPECTS FOR CO_2 FLOODING HETEROGENEOUS RESERVOIRS

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OBJECTIVES

The objective of this work is to improve the effectiveness of CO_2 flooding in heterogeneous reservoirs. Our intent is to investigate new concepts that can be applied by field operators within the next two to five years. Activities will consist of experimental research in three closely related areas: 1) further exploration of the applicability of selective mobility reduction (SMR) in the use of foam flooding, 2) possible higher economic viability of floods at slightly reduced CO_2 injection pressures, and 3) taking advantage of gravitational forces during low IFT, CO_2 flooding in tight, vertically fractured reservoirs.

Task 1 of this project is based on work performed during the recent "Field Verification of CO_2-Foam" (DOE/MC26031) and on a previous project, "Improvement of CO_2 Flood Performance" (DOE/MC21136). In those research projects, as well as in projects reported by other researchers, we have found evidence for SMR when using certain surfactants in mobility experiments in which CO_2 and surfactant solution were pumped simultaneously through core samples cut from rocks of different permeabilities. Experiments that would decisively define the conditions under which SMR could be reliably realized in CO_2 floods could increase present productivity and add millions of barrels to the reserves of many oil fields in the Permian Basin, and elsewhere that CO_2 is available.

The objective of Task 2 of the project is to demonstrate the feasibility of decreasing CO_2 requirements for CO_2 flooding. At a constant temperature, the density of CO_2 decreases with decreasing pressure, thus achieving reservoir fill volume with the same mass at a lower pressure. For some pressure ranges, the change in volume over a relatively small pressure variation is substantial. This effect is common near the minimum miscibility pressure (MMP) in many reservoirs. Micromodel tests at the PRRC have shown high recoveries at pressures near the MMP, with CO_2 densities as much as 70 percent less than densities at the customary flooding pressure. The micromodel study also found significant increases in recoveries below the MMP when CO_2 injection alternates with brine (WAG, water/brine alternating with gas) or surfactant solution (SAG, surfactant solution alternating with gas). Thus, mobility control could decrease concerns of reduced recoveries near or below the MMP because of gravity override, viscous fingering, and reduced solubility.

Task 3 of the project falls under the broad topic, "Low IFT Processes," and is directly related to all EOR techniques that rely on reduction of interfacial tension for mobilization of residual oil. Miscible or near-miscible oil recovery processes, whether surfactant flooding or gas injection processes near the MMP, ultimately depend on reduction of interfacial tension between the resident and injected fluids. The approach to miscibility from an initially immiscible situation involves important consequences regarding dynamic lowering of the IFTs and subsequent alteration of the capillary pressure, P_c, and the Leverett J-function. These important parameters, in turn, determine the relative permeability function used for reservoir simulation.

Knowledge of the mechanism of IFT lowering is important for simulation of EOR processes. For instance, the Parachor Method is currently used as a prediction tool of IFT in multicomponent mixtures. The accuracy of the Parachor Method is limited and has been the subject of criticism, although there has been no rigorous study demonstrating the success or failure of the Parachor Method under widely differing conditions. The IFT and the density difference between the phases as miscibility is approached are the measured parameters in evaluation of the parachor. IFT vs. density difference is also crucial in evaluating capillary-gravity equilibrium in fractured reservoirs, yet there is little understanding of the theory behind the Parachor Method and almost no literature concerning measurement of low IFT CO_2/crude oil mixtures. We hope to refine the use of the Parachor Method and apply the results to the prediction of measured IFTs of crude oil/CO_2 mixtures using only an equation of state (EOS), and ultimately, correlate IFTs with the MMP of selected oils. A supplementary, but equally valuable task to the proposed research, will be the creation of a CO_2/crude oil database, which will eventually be necessary for future CO_2 floods. The following plan is a list of activities for Task 3: 1) Design a pendant drop apparatus for measuring IFTs (oil/water, oil/gas, gas/water) under a wide range of reservoir conditions; 2) analyze the ability of flash routines to predict liquid and vapor densities for calculation of IFTs (Parachor Method) of near miscible, multicomponent mixtures (CO_2/oil, N_2/oil, gas condensate); and 3) correlate IFT and minimum miscibility pressure (MMP) in simple systems and crude oils from measured IFTs (pendant drop) and slim tube experiments.

SUMMARY OF TECHNICAL PROGRESS

Task 1 — SMR Study in CO_2-Foam

A news article prepared for the 1994 summer issue of the PRRC Newsletter (for distribution to operating oil companies) defines our needs for a particular type of heterogeneous reservoir core for use in our study of Selective Mobility Reduction (SMR). For our experiments, we require several full cores in each of which a sharp transition exists, between a higher and a lower transition zone. We will explore and define more closely the extent and geometry of the transition zone, and the permeability ratio across it, by use of the PRRC scanning minipermeameter. From each of these cores, we will cut a cylindrical core plug sample in which a diametral plane separates the two zones.

We have made tentative designs of a special core holder that we will construct, which will make possible the simultaneous measurement of mobility in the two parallel halves of the core plugs described above. The purpose of these measurements will be to determine whether the mobilities of the two halves will remain in proportion to the permeabilities. If SMR is present, the mobilities will be little affected by the permeability, and the ratio of the measured mobilities will be near to unity, even for cores in which the permeability ratio is large. We and others have observed SMR in laboratory experiments with separate cores of different permeabilities — but this will be the first study with actual reservoir rock, in which the two permeability zones are in capillary contact. Naturally, for our study to be complete, these experiments will be repeated at many different overall flow rates, and with different surfactants and types of cores.

Task 2 - Reduction of the Amount of CO_2 Required in CO_2 Flooding

Experimental Phase Behavior Tests

Seven constant composition expansion tests were performed at 138°F on a West Texas reservoir oil, with each test having an increasing concentration of CO_2. The CO_2 concentration ranged from 0.0 to 72.7 mole %. This oil is from a naturally fractured reservoir and, consequently, of great interest for work in Task 3. This reservoir oil will be used in future coreflood tests and fulfills the requirement of this task of having a fluid tested at a reservoir temperature above 120°F where a three-phase region is not expected.

The initial oil was separator oil recombined with separator gas to a bubble point of about 1900 psig. The saturation pressure, volume, and density of the system increased with an increasing mole % of CO_2. The increase in density was due to the negative excess volumes of mixing of oil and CO_2 plus an increase in pressure. Comparing undersaturated systems at a constant pressure, the density increases with the addition of CO_2. For example, a mixture of 38.8 mole % of CO_2 with oil has a bubble point at about 2558 psig and a density of 0.795 g/cc, while the density of CO_2 at 2500 psig is 0.677 g/cc and the density of the recombined oil is 0.764 g/cc. It is a common and interesting phenomenon that the density of an oil/CO_2 system is often greater then either of the major components.

Reservoir Simulation Studies

CO_2-foam features are being incorporated into reservoir simulators. The reservoir simulators used in this work include a compositional reservoir simulator, UTCOMP, provided by the University of Texas at Austin and a multi-component pseudo-miscible reservoir simulator, MASTER (Miscible Applied Simulation Techniques for Energy Recovery), obtained from the Department of Energy.

A foam model is being developed in UTCOMP by using the tracer features and treating the surfactant solution as an aqueous tracer without the addition of a surfactant-solution conservation equation. The tracer adsorption model has been modified to account for the adsorption isotherm. Instead of using a mechanistic approach to calculate the mobility of the gas-foam phase, the foam model reads as input the foam-resistance-factor (ratio of total mobility of gas and water with surfactant in the aqueous phase to the system without surfactant) data as lookup tables. In the lookup tables, the resistance factor is a function of interstitial velocity, gas-liquid ratio, and surfactant concentration based on laboratory test results. The creation of foam depends on the gas-, oil-, and water-phase saturations and the surfactant concentration. If any of these conditions do not meet predetermined limits, foam is not formed, and the gas-phase mobility is not modified. Foam is assumed to have no effect on the water phase, and the mobility of the gas-foam phase is a function of the resistance factor, water mobility, and gas mobility before foaming. The resistance factor represents the pressure drop attributed to the presence of foam; and without foam, the resistance factor is unity.

Major modifications that were made to MASTER include (1) the addition of two conservation equations to permit simulation of surfactant solution and foam bubbles, (2) the addition of an algorithm to calculate the mobility of gas-foam phase, and (3) the addition of a foam-resistance-factor table-lookup option similar to the one incorporated into UTCOMP. The mobility of gas-foam phase can be calculated by using the foam-bubble population balance equation option or the foam-resistance-factor table-lookup option.

To assess the sensitivity and adequacy of the foam features in UTCOMP, we are currently running tests on a three-dimensional quarter of a five-spot pattern in a reservoir divided into five layers. Prior to each foam test in the model, the reservoir is water flooded for ten years and CO_2 is injected for five years. Then each test has a one-year foam treatment where surfactant is injected for 122 days to satisfy absorption, followed by a 90-day rapid SAG injection of 6 cycles each consisting of 3 days of surfactant solution injection and 12 days of CO_2 injection, and finally 153 days of CO_2 injection.

Task 3 - Low IFT Processes and Gas Injection in Fractured Reservoirs

A pendant drop apparatus has been designed for measuring surface and interfacial tensions for oil/water, gas/water, and gas/oil systems under reservoir conditions. The apparatus is currently being constructed.

We have analyzed the ability of flash calculations to estimate liquid and vapor densities of multicomponent mixtures, which in turn, are used to calculate IFTs by the Parachor Method. We have completed an exhaustive literature survey of all measured IFTs at near miscible conditions for CO_2/oil, N_2/oil, and gas condensate systems.

A computer code has been developed that combines flash routines with the Parachor Method. We have used this program to predict all the aforementioned published measurements of IFTs. There has been speculation that IFTs are poorly predicted at near miscible conditions. We have shown that, in general, the Parachor Method is a robust technique for prediction of low IFTs for many simple systems. For example, Fig. 1 shows comparisons between calculated and measured IFTs for two synthetic oil systems that recently appeared in the literature. The calculations were made by using the Peng-Robinson Equation of State and the Parachor Method.

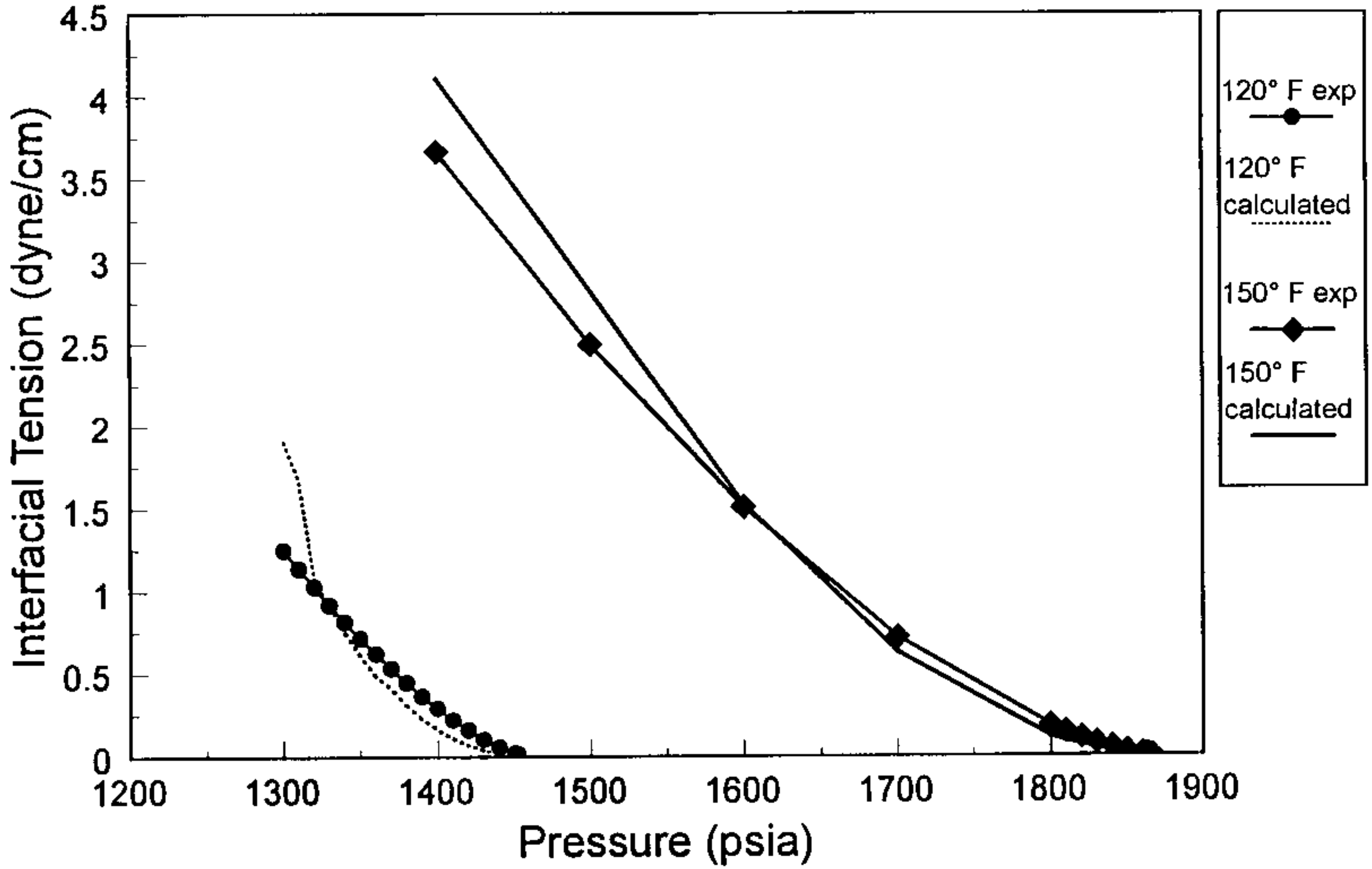

Fig. 1. IFT vs. pressure for CO_2/synthetic oil system: measured data compared with equation of state calculation.